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Abstract

A new mode of operation for ionization detectors is described. The amount of ionization produced in a detector is determined by measuring the amount of heat generated during the carrier collection process. Very high detection sensitivities, including single carrier detection, may be achieved at cryogenic temperatures. Results from an experimental device operated at $T=0.3$ K is presented.

1. Introduction

In an ionization detector, the energy deposited by incoming radiation is determined by measuring the amount of ionization produced which is given by:

$$N = E / \epsilon \quad (1)$$

where N is the average number of pairs of charged carriers produced, E is the deposited energy and ϵ is the average energy expended in creating one pair of carriers. The r.m.s. statistical variation in N is given by $\sqrt{FE/\epsilon}$, where F is the Fano factor. This corresponds to an r.m.s. fluctuation of the measured energy given by:

$$\sigma_E = \sqrt{FE\epsilon} \quad (2)$$

The energy resolution of a detector system is the quadrature sum of this statistical term and the noise associated with the measurement electronics. Since the statistical contribution is proportional to \sqrt{E} , the electronic noise can dominate the energy resolution of a detector at low energies. In addition, because of interference from the electronic noise, events below a certain energy cannot be reliably detected. Semiconductor detectors exhibit the lowest values of ϵ (3 eV for Ge, 3.6 eV for Si) and F (≈ 0.1 for Ge and Si) and thus provide the best energy resolution and the lowest detection threshold energy among ionization detectors.

Traditionally, the amount of ionization created in a detector is measured using amplifiers which respond to the induced current arising from the collection of carriers. The lowest electronic noise level achieved in state-of-the-art semiconductor detector systems is ≈ 50 eV FWHM. This limits the detection threshold above the noise tail to ≈ 150 eV. Major improvements over this value seemed difficult using direct ionization charge measurement techniques. However, a very large

improvement can potentially be made using low-temperature calorimetric technique to detect the number of ionization carriers [1]. With this technique, it may be possible to achieve electronic noise levels lower than the signal arising from a single pair of carriers. This will make the contribution of electronic noise to the energy resolution negligible, thus allowing ionization-statistics-limited detection down to very low energies. It may also be possible to use such detectors as single photon counters for photon energies extending down to the near infrared. Besides the obvious applications in low-energy X-ray spectroscopy and faint light detection, such detectors will also be of interest in dark matter particle search experiments [2] and possibly in the detection of neutrinos via the coherent nuclear scattering process [3].

2. Principle of Operation

In a calorimetric ionization detector, the amount of ionization generated by an event is determined by measuring the heat produced during the collection of charged carriers. The total amount of energy dissipated by each carrier is simply the product of its charge and the potential drop it has traversed. Assuming that all the energy goes into thermal excitation and that the carriers are fully collected, the total amount of thermal energy generated by radiation depositing an energy E in the detector is given by:

$$E_t = \frac{E}{\epsilon} e V_d + E \quad (3)$$

where V_d is the voltage across the detector. The last term represents the heating effect of the radiation itself. The part of E which is consumed initially to create the ionization is recovered as long as the carriers are fully collected at degenerate (metallic) contacts of the detector. (The

equivalent formula given in Ref. [1] was incorrect as it ignored this fact). The value of E_t can be determined by measuring the temperature rise of the detector given by:

$$\Delta T = \frac{E_t}{C} \quad (4)$$

where C is the heat capacity of the detector. Although, in general, C is a function of temperature, the above equation is a good approximation for small ΔT . In a practical device, there will be a weak thermal link between the detector and a cold bath so that the detector will return to an equilibrium temperature after an ionization event. The basic structure is similar to passive calorimeters which measure only the heat resulting from the thermalization of the energy deposited by the radiation, and the same thermal noise analysis can be used.

For a passive calorimeter, the lowest uncertainty in energy measurement is obtained when the system is phonon-noise limited. The phonon or thermodynamic noise, expressed as r.m.s. temperature fluctuations and integrated over all frequencies is given by $\sqrt{k_B T^2/C}$, where k_B is the Boltzmann constant, T is the temperature and C is the heat capacity of the detector. For low temperature calorimeters, temperature measurement is commonly made using semiconductor thermistors which exhibit large values of dR/dT , where R is the resistance of the thermistor. Johnson noise of the thermistor contributes to the measurement noise of the calorimeter. It has been shown that, using a semiconductor thermistor, the total thermal measurement noise of a passive calorimeter for pulse detection under optimum operating conditions can be expressed as [4]:

$$\sigma_T = \xi \sqrt{k_B T^2/C} \quad (5)$$

where ξ is a numerical constant whose value depends on the responsivity of the thermistor. For values of responsivity obtainable from existing semiconductor thermistors, $\xi \approx 2$. The corresponding r.m.s. energy noise is given by $\sigma_E = \xi \sqrt{k_B T^2 C}$. For pure dielectric crystals at low temperatures, $C \propto MT^3$, where M is the mass of the crystal. Therefore, at low temperatures, σ_E can be made very small. A noise level of 11 eV FWHM has been reported [5] but it was obtained for a detector with an active volume of only $2 \times 10^{-5} \text{ cm}^3$ while operating at $T = 0.098 \text{ K}$. If the deposited energy is completely thermalized, the energy resolution of a passive calorimeter is limited only by the thermal measurement noise.

Unlike passive calorimeters, the energy resolution of a calorimetric ionization detector is ultimately limited by ionization statistics. On the other hand, the amount of heat generated by an event is $1 + eV_d/\epsilon$ times the energy deposited by the radiation itself while the thermal measurement noise is still given by eq. (5). Combining with eqs. (3) and (4), the electronic noise for the calorimetric ionization detector, expressed as r.m.s. fluctuation of the measured radiation energy can be written as:

$$\frac{\xi \sqrt{k_B T^2 C}}{(1 + eV_d/\epsilon)} \quad (6)$$

To achieve the same effective energy threshold at the same operating temperature, the thermal mass of the calorimetric ionization detector can be made much larger than that of the passive calorimeters simply by increasing the collection voltage, V_d . At sufficiently low temperatures, the electronic noise can be made very small. For example, the calculated electronic noise for a detector made from 1 cm^3 of Ge operating at $T = 0.1 \text{ K}$ and $V_d = 3000 \text{ V}$ is only 0.3 eV FWHM, for $\xi = 2$ and $\epsilon = 3 \text{ eV}$. An electronic noise level below ϵ means that a single pair of ionization carriers can be detected. Since the electronic noise is, in principle, independent of the number of carriers, it

should be possible to determine accurately the number of carriers produced by an event, thus enabling ionization-statistics-limited detection for any low-energy ionization events.

3. Experimental

The principle of calorimetric detection of ionization was first demonstrated experimentally with a detector operating at 1.8 K [1]. The detector consisted of a $(5\text{mm})^3$ high-purity Ge p-i-n diode with a $(0.25\text{mm})^3$ neutron transmutation doped (NTD) Ge thermistor as the temperature sensor. Signals arising from alpha particles were detected and the expected gain in signal with increasing bias was observed. Because the signal filter and the thermistor were far from optimum, the effective electronic noise obtained at a diode bias of 1000 V was ≈ 50 keV FWHM, whereas a noise level of ≈ 1 keV FWHM should have been possible for the detector parameters used.

Another detector designed for operation at 0.3 K was fabricated and tested in a He^3 cryostat. Fig. 1 shows schematically the structure of the detector. The active mass is a 1mm^3 p-i-n diode made from Ge with a net donor concentration of $1 \times 10^{11} \text{ cm}^{-3}$. The p+ and n+ contacts were formed respectively by ion implantation of boron and phosphorus. The NTD Ge thermistor was fabricated from material designated as NTD#5 which should give $dR/dT = 5 \times 10^9$ ohms/K at zero bias [6]. It was attached to the p-type contact of the diode using indium, thus sharing a common electrical connection with the diode. One mil diameter brass wires acting both as electrical connections and mechanical support between the diode-thermistor and the substrate were attached using electrically conductive epoxy [7]. The heat capacity of the Ge at 0.3 K is $7.5 \times 10^{-11} \text{ J/K}$ while that of the other attachments is estimated to be $2 \times 10^{-10} \text{ J/K}$. The thermal conductance of the brass leads is $\approx 1.5 \times 10^{-7} \text{ watt/K}$ which gives a thermal decay time-constant of ≈ 1.8 msec.

The circuit used is shown schematically in Fig. 2. The input FET of the amplifier was mounted inside the He^3 cryostat and is maintained at a temperature of ≈ 120 K. The bypass capacitor kept the voltage across the thermistor constant during a pulse [8]. Signals from the circuit were further amplified and filtered using a pseudo-gaussian shaper with a time constant of 1.2 msec.

Figure 3 shows spectra obtained using an Am^{241} source with the detector operating at 0.3 K. The operating conditions were kept unchanged except for the diode bias. Linear increase in signal amplitude with increasing bias voltage can be seen. A spectrum obtained with zero diode bias and with 17 times higher amplifier gain is shown in Fig. 4. With zero bias, the detector acted as a passive calorimeter. The noise of the system as measured using an r.m.s. voltmeter connected to the output of the shaping amplifier remained constant with increasing bias until $V_d > 140\text{V}$ at which point the noise began to increase sharply, presumably due to the onset of excessive leakage current (Fig. 5). The maximum signal-to-noise ratio, obtained at $V_d = 140\text{V}$, corresponds to an electronic noise of 160 eV FWHM.

Based on the value of dR/dT of the thermistor and the heat capacity of the detector, it should be possible to obtain an electronic noise level of ≈ 10 eV FWHM at $V_d = 140\text{V}$. The much higher noise level measured is attributed mainly to the non-ideal behavior of the thermistor. It is known that the value of dR/dT of semiconductor thermistors can decrease drastically even in the presence of a small bias voltage, especially at low temperatures [9], and thereby decreases the signal-to-noise ratio. There is evidence to suggest that higher dR/dT can be obtained with thermistors made from lower resistivity materials and using larger inter-electrode distances to minimize the electric field within the device. A systematic study of the behavior of semiconductor thermistors as a function of bias, temperature and doping level is required for proper optimization of the detector.

Even without further optimization of the thermistor, a direct gain in the signal-to-noise ratio can be realized by increasing the operating voltage of the diode. The apparent onset of excessive leakage current in the present device at $V_d > 140\text{V}$ is most likely due to the phosphorus implanted contact of the diode. The contact was fabricated using the same procedures as for Ge charged-particle transmission detectors which operate at liquid nitrogen temperatures [10]. This type of contact was known to exhibit electrical breakdown at a much lower electric field compared to contacts made by lithium diffusion. The latter was not used here because of the concern that the resulting lower dopant concentration may cause the contact to freeze-out at the low operating temperature. On the other hand, the presence of a high electric field may keep enough dopant ionized for the contact to function. In any case, it should be possible to develop better contacts to enable the detector to operate at a much higher voltage.

In the spectrum obtained at $V_d = 140\text{V}$, the width of the 59.5 keV gamma ray peak is 600 eV FWHM. The resolution expected for an electronic noise level of 160 eV FWHM and assuming $F=0.1$ is 320 eV FWHM. The exact reason for the discrepancy is not clear at the present time but it may be the result of carrier trapping since the shallow impurities in the Ge crystal can become effective traps at the low operating temperature. Trapping effects have been observed with the earlier device operating at $T=1.8\text{ K}$ but was seen to be largely ameliorated at high operating voltages [1].

4. Conclusion

Low-temperature calorimetry has been applied as an alternate technique for the measurement of ionization in a detector, with the capability of achieving very low electronic noise. An experimental device operating at 0.3 K has achieved an electronic noise level of 160 eV FWHM. With further

optimization of the thermistor and by increasing the operating bias of the diode, a much lower noise level is expected.

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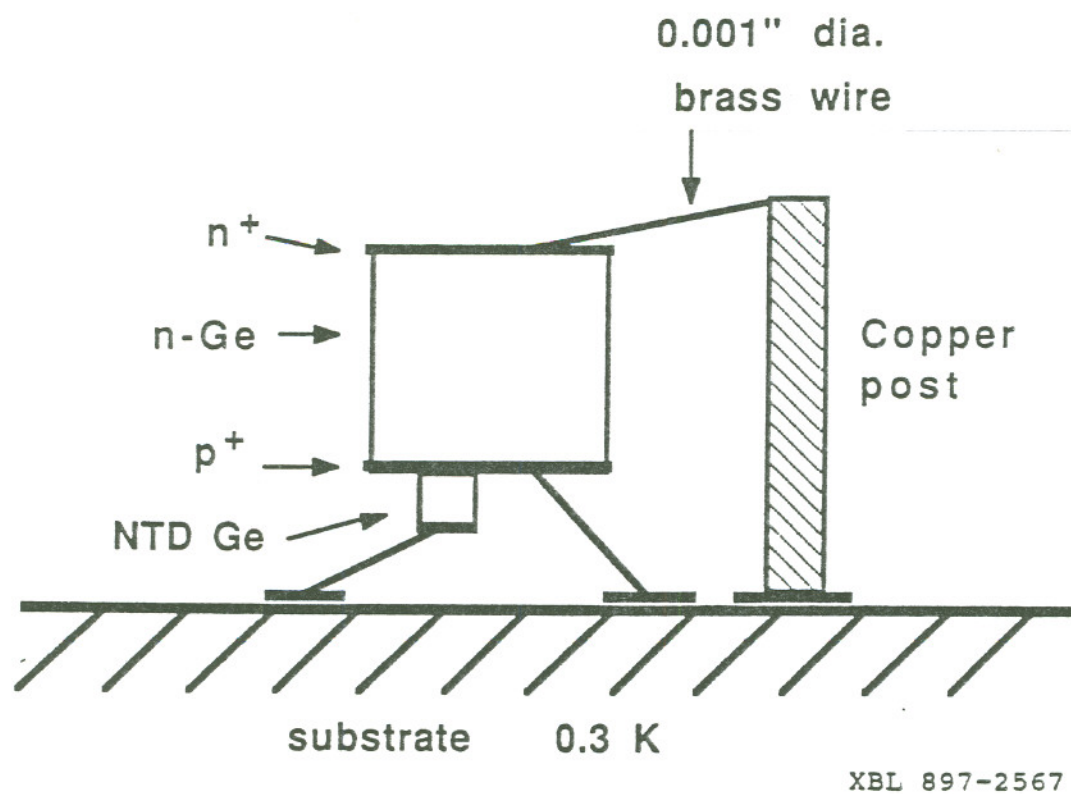
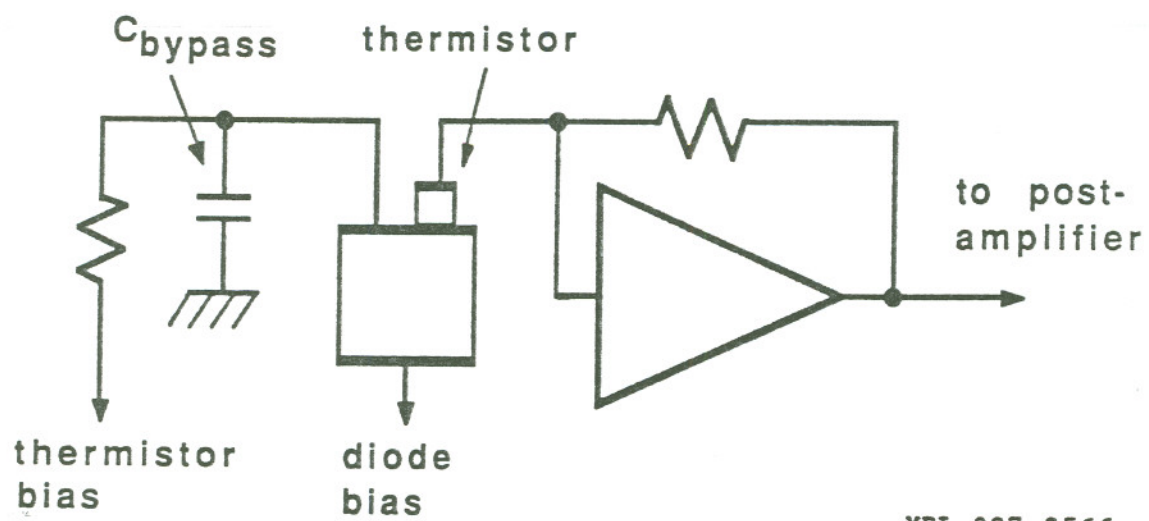


Fig. 1 Schematic structure of the detector.



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Fig. 2 Electrical circuit used in the experiment.

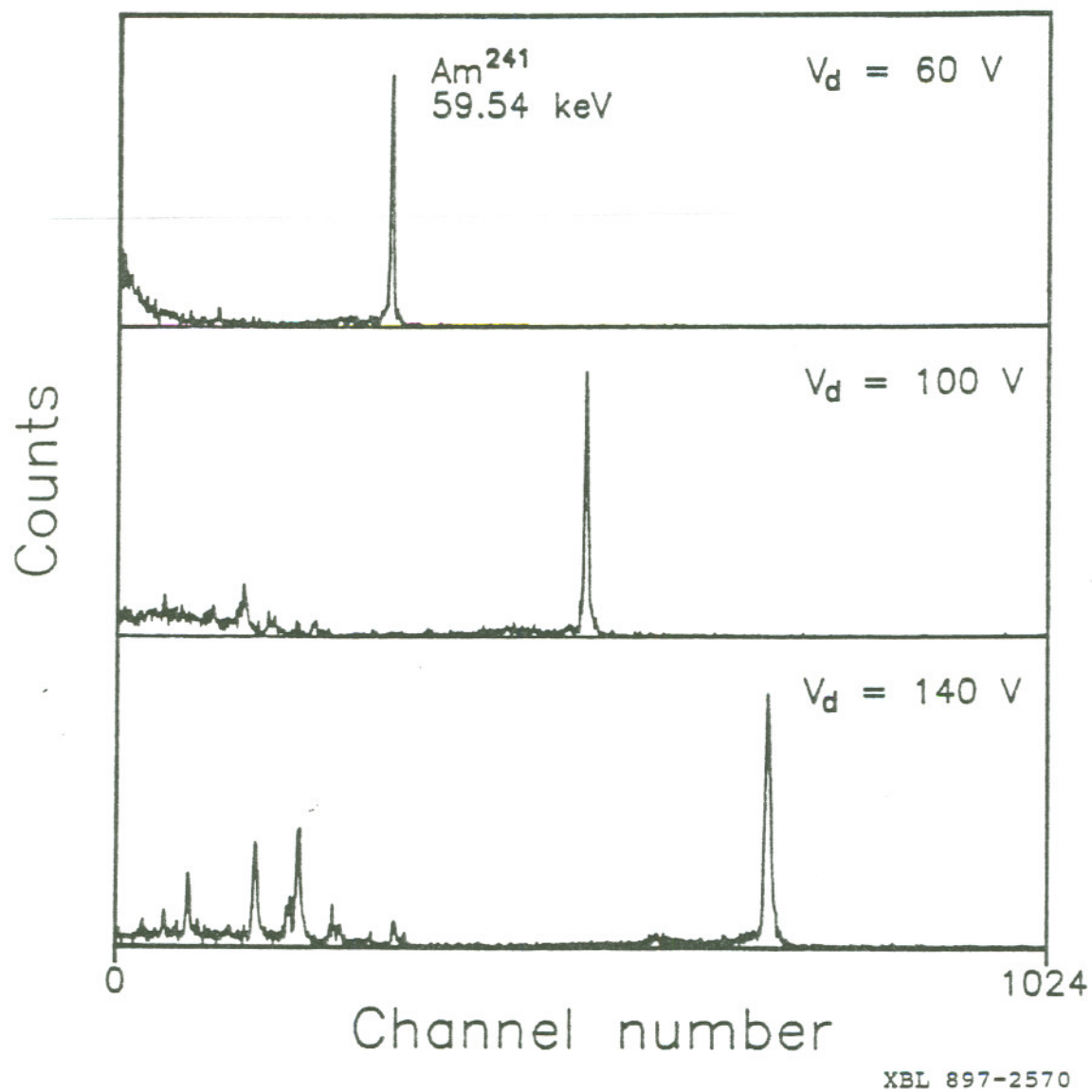


Fig. 3 Spectra obtained using an Am^{241} gamma ray source at different diode voltages.

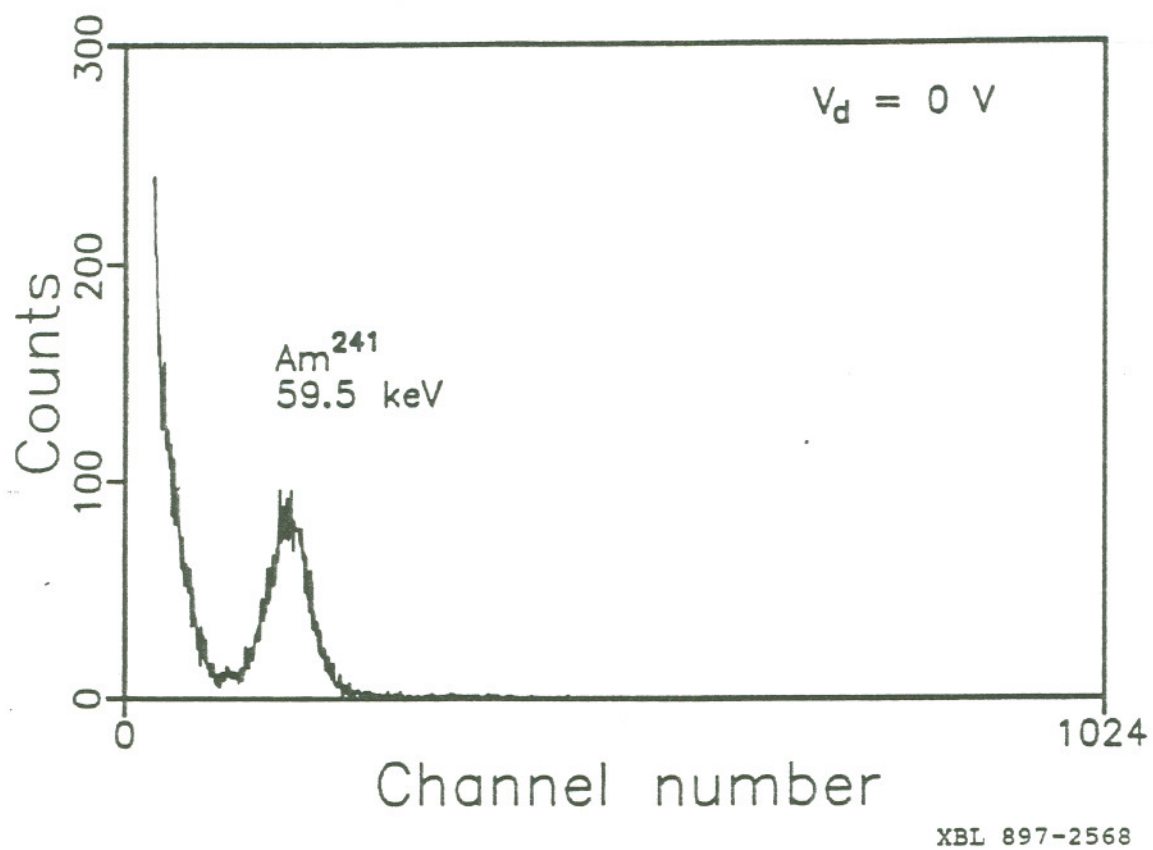
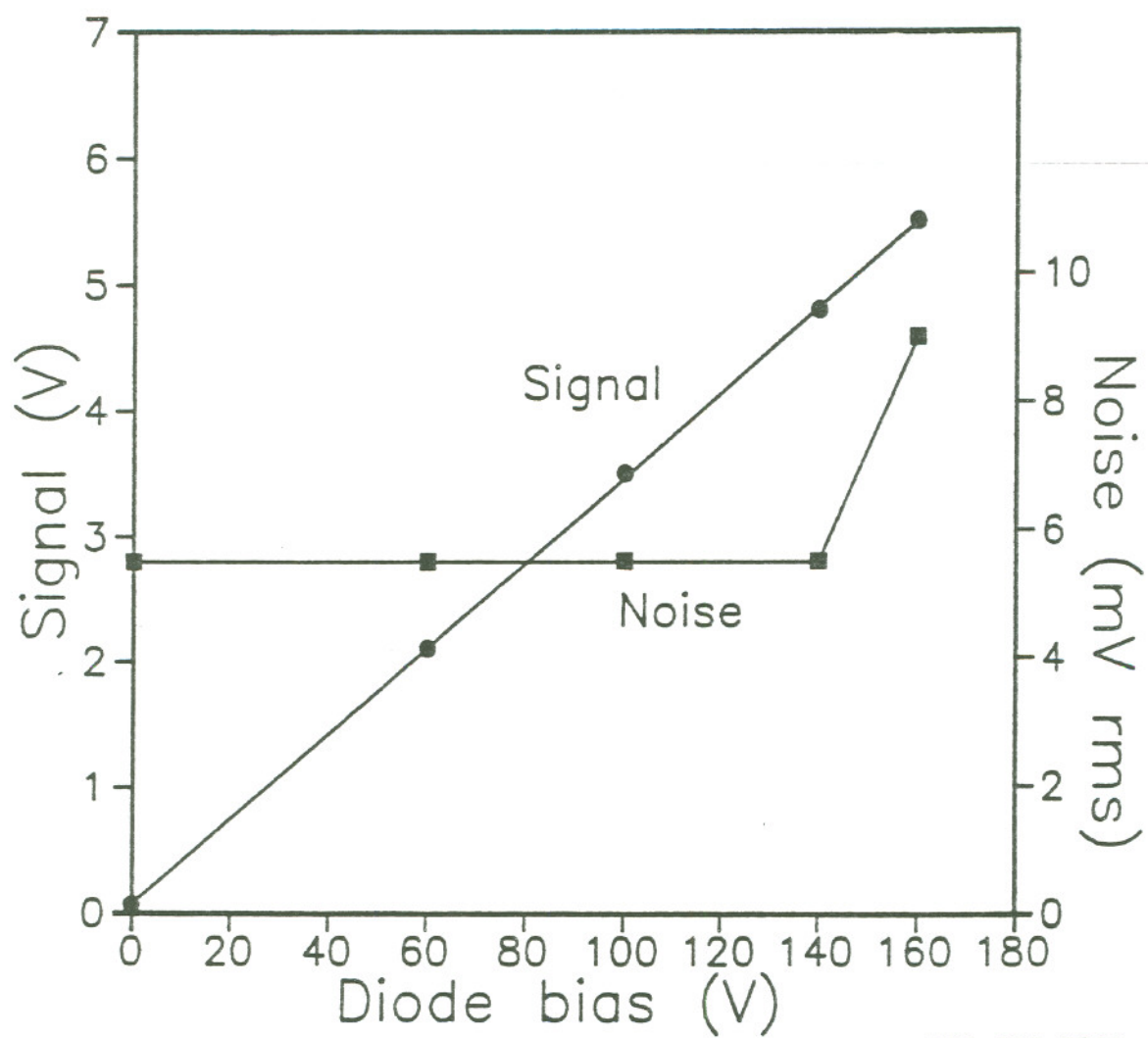


Fig. 4 Spectrum taken at zero diode voltage. The amplifier gain is 17 times higher than that used to obtain the spectra in Fig. 3.



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Fig. 5 Signal amplitude and r.m.s. noise as a function of diode voltage.